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Wind farm performance

Power Analysis of a wind turbine

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Master's Thesis
Submission date: June 2016
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Norwegian University of Science and Technology
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NTNU
Norwegian University
of Science and Technology

Department of Energy
and Process Engineering

EPT-M-2016-167

MASTER THESIS

for

Student
Alejandro Esquinas Herrera

Spring 2016

Wind farm performance

In order to develop the low-order tools needed to control individual wind turbines (WT) in a wind farm (WF) it is necessary to understand the key physics that need to be modelled and experimental data to calibrate and validate the model. For full-scale WFs there is a lack of experimental data, especially where all necessary parameters are controlled and measured. Therefore, one has to depend on model-scale experiments as benchmark cases (Krogstad et al., 2013, 2014; Pierella et al., 2014). The question of "scaling" of results from model scale to full scale needs to be addressed. Røkenes and Krogstad (2009) did a detailed and documented wind tunnel study of wind over a model terrain containing typical terrain formations of a WF. Such studies need to be extended with measurements both in model and full scale of the same WF. Scaling is also and important issue for control and optimizing performance for a single turbine. Model studies are well controlled, but there are significant uncertainties about scaling effects – e.g. Reynolds number effect on Lift, Drag and stalling characteristics for the airfoils used as rotor blades. Krogstad and Adaramola (2011) have investigated effects of pitching the blades and yawing the rotor w.r.t. incoming wind direction. The development of scaling methodologies requires that these types of investigations are performed at full scale such that they will be useful for the calibration of theoretical simulation models.

For the present study we have access to a 3-turbine wind farm with Vestas V27 turbines. The 3 WTs are located nearly on a straight line, thus enabling an evaluation of the performance of a turbine when it is exposed for an undisturbed wind, and when the turbine is located in the wake of an upwind turbine. The evaluation can be extended to address the "scaling problem" by comparison with the model scale studies cited above. For the measurement of wind characteristics there is deployed a Windcube v2 Lidar at the WF site, and a data-logger is to be installed at one WT to measure parameters for the WT performance.

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

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☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
X Field work

Department of Energy and Process Engineering, 08.02.2016

Olav Bolland
Department Head

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Department of Energy and Process Engineering

TEP4925 - Engineering Fluid Mechanics, Master's Thesis

Ørland, Norway: Wind farm performance

Alejandro Esquinas Herrera

ABSTRACT

Wind conditions from a wind farm situated in Ørland were analyzed based on a ten minute measurements in order to obtain the power and efficiency curves. The results from the analysis were compared with different curves provided from the company Vestas and with theoretical terms. Moreover, it was shown how is affected the power curve of the wind turbine by the wake effect of the other turbines. The different ways of plotting these curves based on wind speed either from the anemometer of the wind turbine or through Windcube v2, a device that provides information about the wind conditions of the location, were discussed.

I. Introduction

Wind energy is an abundant resource, renewable and clean, which helps reducing greenhouse emissions by replacing energy sources based in fuel. The environmental impact of this type of energy is also generally less problematic than other energy sources. These facts are increasing the installation of more modern and profitable wind farms either in large scale or small scale like in this case. In order to obtain the best efficiency of this resource is important to analyze its potential experimentally and ensure the best situation for its deployment.

II. Site description

In Ørland, there is a wind farm situated among agricultural fields close to the fjord with scattered buildings but no tall structures in proximity. Therefore, based on in the criteria of MEASNET (1) the surroundings can be classified as “simple terrain”. The coordinates of this location are: N 63.701728 E 9.653007. The wind farm consists of three wind turbines by the company Vestas, they are of the type Vestas V27 and were installed in 2003. Information used in this report was obtained from the wind turbine situated in the middle as seen in Fig. 1.

Figure 1. Wind farm in Ørland.

III. Windcube v2

A Windcube v2 is located close to the wind farm near to the warehouse (Red building, Fig.1) This device measures the wind components (wind speed, wind direction, temperature) up to 200 m height (in this case until 40m). The data acquisition of it is based on LIDAR (Laser Imaging Detection and Ranging). LIDAR is widely used in several applications such as geology, seismology, weather assessment. It is available in different variations (continuous wave LIDAR, direct detection LIDAR…). Here, it was used to obtain the wind conditions of the location using a Doppler Lidar. Doppler LIDAR are used to measure temperature and/or wind speed along the beam by measuring the frequency of the backscattered light. The system transmits a laser beam into the air, receives the light backscattered by aerosols, and analyzes the atmospheric properties using the received signal. The signals from moving objects have a Doppler shift proportional to their speed, which enables the velocity of the aerosols to be calculated. As a result, the direction and speed of the wind can be measured (2).

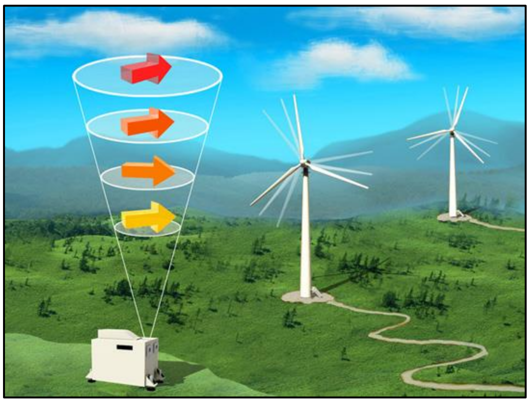

Figure 2. LIDAR technology.

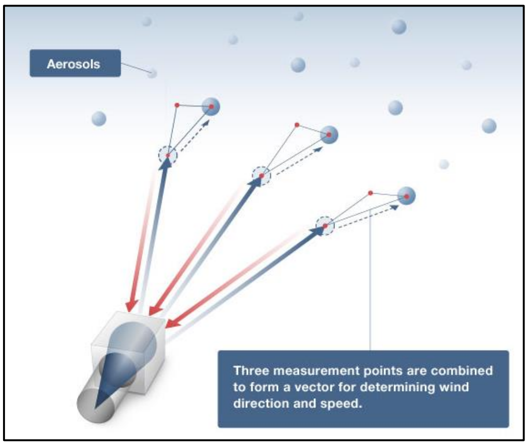

Figure 3. Measurement principle.

IV. Wind in Ørland

The wind analysis is based on measured data of one year, from May 2015 to May 2016. The data was taken by Windcube v2 with 10-minute average samples (1). Measurements were treated by Windographer, a software for analyzing wind resource data measured by met tower, SODAR, or LIDAR. It allows quality control and statistical analyses including MCP (Measure Correlate Prediction).

The Windographer gave information on the main direction of the wind and the wind speed of each month in order to define the favorable position and months for the wind farm. As seen in Fig. 4, the wind was coming mainly at 135 º (south-east direction). In this case, this means that the wind was coming from the beach. (Fig. 5, right bottom corner).

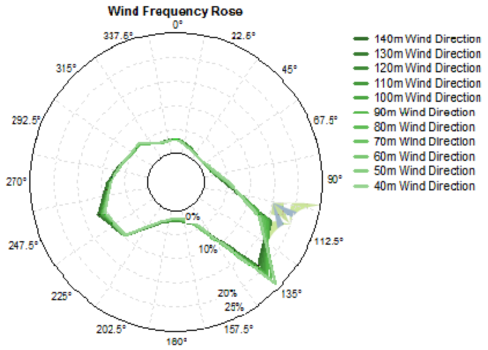

Figure 4. Wind rose in Ørland.

Figure 5. Wind rose in Ørland.

In Fig. 6, monthly data on wind speed given out by the software is displayed and it can be observed that the highest wind speeds occurred in November and January when it reached almost 14 m/s.

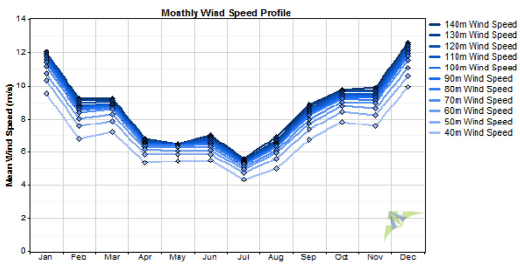

Figure 6 Monthly wind speed distribution.

Year	Mean wind speed (m/s)	class
May-15	6	2
Jun-15	5.8	2
Jul-15	4.58	1
Aug-15	5.56	1
Sep-15	7.3	4
Oct-15	8.3	6
Nov-15	8.2	6
Dec-15	10.6	7
Jan-16	10.4	7
Feb-16	7.5	6
Mar-16	7.8	6
Apr-16	5.8	2
May-16	5.6	2

Figure 7. Monthly wind power class.

Fig.7 Shows monthly mean wind speed (50m. height) of the months that Windcube v2 had obtained data for this analysis. As is said before the best months are in winter with outstanding values of wind power class. However, there are several months were the mean values are low classified. Furthermore, Windographer obtained the mean annual value of the wind speed at 50 m. 6.83 m/s with a wind power density of 478 W/m2, which is categorized as wind power class 4 (5).

The diurnal wind speed profile is illustrated in Fig 8. It seems that the wind does not change during the day. However, this assumption it is not true. The graph only represents the annual mean. The only conclusion of this result is that there is no focus on the wind on any daytime in the average.

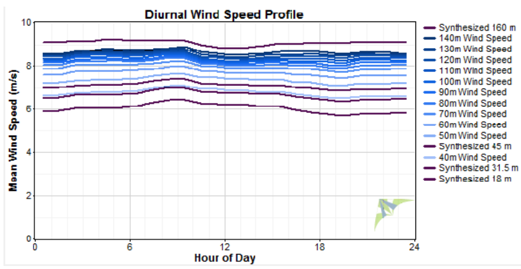

Figure 8 diurnal wind speed distribution.

Fig. 9 describes the wind profile in the location. The wind profile slightly varies from the bottom of the blade (18 m.) until the top of it (45m.). Fig.10 confirms the thin dispersion of the profile at the two different heights with a strength correlation R = 0.96. However, in order to rise the viability of the results, this will be taken into account in the following points.

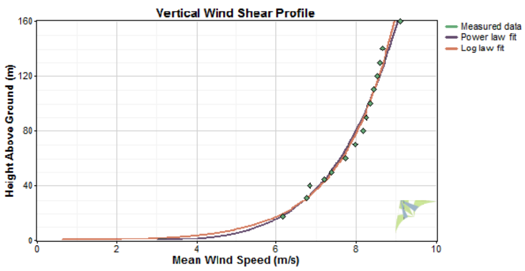

Figure 9. Wind profile Ørland 2015-2016.

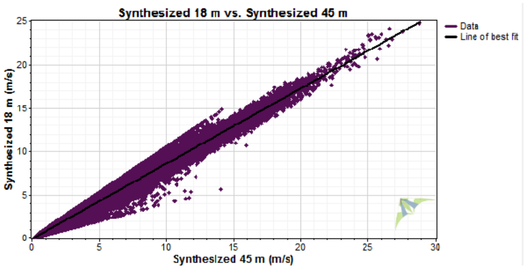

Figure 10. Scatter plot between 18 and 45 m. height.

V. Weibull distribution

The Weibull function is the probability density function used to describe wind speed data is (3):

$$f(v) = \left(\frac{k}{c}\right) * \left(\frac{v}{c}\right)^{(k-1)} * e^{-\left(\frac{v}{c}\right)^k} \quad (v,c,k>0) \quad 1)$$

Where:

- v = wind speed (m/s).
- f(v) = probability of the wind speed.
- c = scale parameters.
- k = shape parameter.

The maximum estimator for parameter k is:

$$k^{-1} = \frac{\sum_{i=1}^{n} v_i^k * lnv_i}{\sum_{i=1}^{n} v_i^k} - \frac{1}{n} * \sum_{i=1}^{n} lnv_i \quad 2)$$

Where v_i is the wind speed of the i th iteration and n is the number of measurements.

K parameter describes the failure distribution when it is proportional with the time:

- *k*<1 indicates that the failure rate decreases with time.
- *k*=1, indicates that the failure rate is constant with time.
- Un valor *k*> indicates that the failure rate increases with time.

The maximum likelihood estimator for the c parameter given k is (3):

$$c^k = \frac{1}{n} * \sum_{i=1}^{n} v_i^k \quad 3)$$

C parameter determines the dispersion of a probability distribution. If it is large, the distribution will be wider, if not it is more concentrated.

The Weibull density function indicates the probability of a wind speed being within a certain interval width (3):

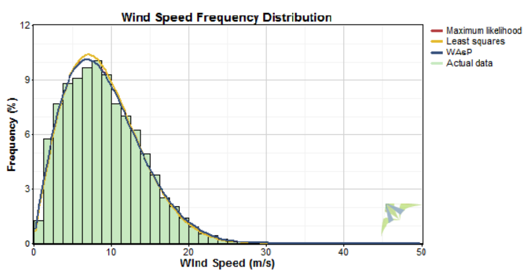

Figure 11. Weibull distribution Ørland 2015-2016.

In this case the values of the parameters were k = 1.753 and c= 10.456 (m/s) respectively. The function fits better with wind speed velocities up to 6 m/s. Although all the results are close.

VI. Long term extrapolation

The wind conditions usually show inter-annual changes. Therefore, due to the lack of data of this site since data has only been retrieved since May 2015 and in order to obtain a better forecast for the assessment of the weather conditions in the location, the data provided by Windcube v2 will be extrapolated for long terms. In the actual, data available from the official weather station from the Meteorologisk institutt situated in the airport, which has a mast 10 meters above the ground and it consists of an anemometer and a vane, is taken as a reference. The coordinates of that location are: N63.666380 E8.342510. Information was taken from 2010 until 2016. The extrapolation was made by Windographer, which applied a Measure Correlate Prediction (MCP) procedure that compares the site data with the reference data set of the las 6 years. Several algorithms are available for calculating the long term extrapolation. Matrix Time Series (MTS) was used in this work because it showed the smallest error for almost all of the parameters (mean absolute error, RMS error and distribution error) (4).

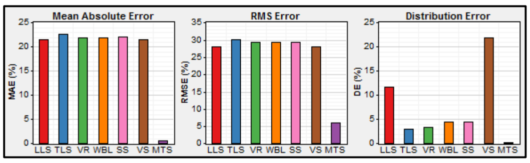

Figure 12. Error´s parameters in algorithms.

The resulting (Long term data 40m.) wind frequency rose, monthly wind speed profile, wind speed frequency distribution, wind profile with the short term period (Short term data 40m.) and with data provided by Meteorologisk institutt (Reference data) are illustrated in Fig. 13, Fig. 14 and Fig. 15. It reveals a mean wind speed at hub height (31,5) of 6.83 m/s and a mean wind direction of 135º (south-east direction), which can be settled as the approximated mean value for the future. Moreover, it was shown that the wind profiles for long term and short term are almost the same. Fig.14 Describes monthly wind speed profile at 40m. in the different terms of the assessment and it can be seen that are almost the same in all the cases, being windier in winter period and reaching the lowest values in summer.

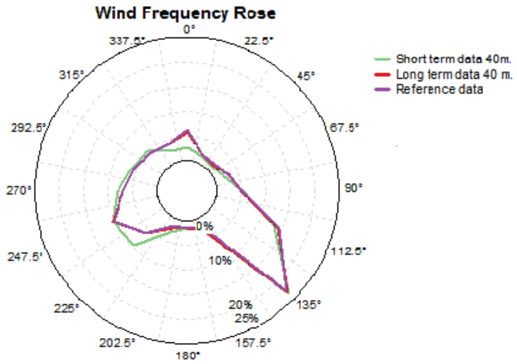

Figure 13. Wind Frequency Rose of Reference Data, Long Term Site Data and Short Term Site Data.

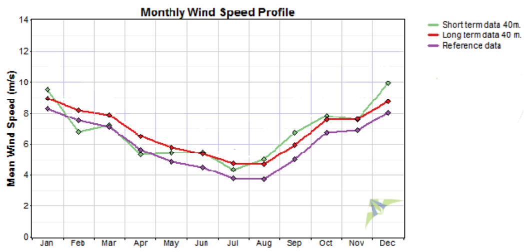

Figure 14. Monthly Wind Speed Profile of Reference Data, Long Term Site Data and Short Term Site Data.

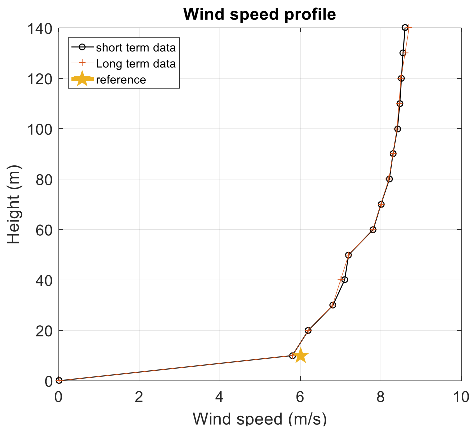

Figure 15. Vertical Wind Shear Profile of Reference Data, Long Term Site Data and Short Term Site.

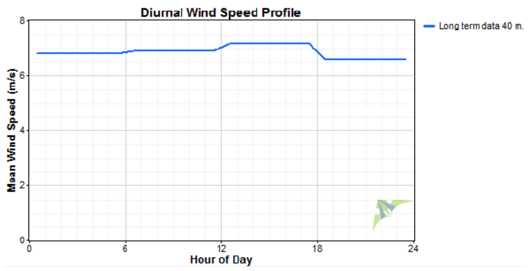

Figure 16. long term data diurnal distribution at 40m.

The diurnal distribution for a long term extrapolation does not change at all during the day. Therefore, as it is said with the short term data. The conclusion is that there is no need to focus in any particular time of the day for the assessment.

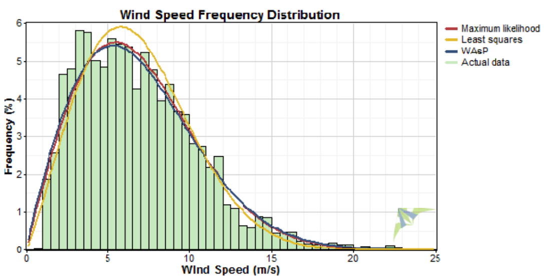

Figure 17. Weibull distribution long term data 40m.

In this case the Weibull distribution discern more from the frequency values of the different speeds than short term data, although it still being quite close up to 6 m/s. The parameter's values are k = 1.985 and c = 7.764 m/s.

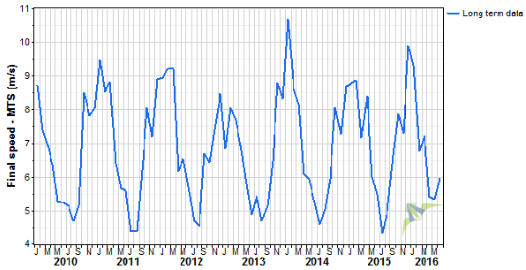

Figure 18. Wind speed patter each year in extrapolated terms.

Data from 1 year in the location of the wind farm has been extrapolated up to 6 years based on data of the Meteorologisk institutt. Fig.18 describes the pattern of those years at 40m. height. It shows the similarity of almost all the years, except between 2012-2013 and 2013-2014 when the values slightly discern form the others.

In order to specify the power class of each year, it is necessary to obtain the mean wind speed at 50 m. height (5). The best year is 2015 with a class of 5 and really close to class 6 with maximum value of 7. In all the cases the mean wind speed reached values that are optimal for a wind farm deployment.

Year	Mean wind speed (m/s)	class
2010	7.03	4
2011	7.56	5
2012	7.56	5
2013	7.21	4
2014	7.63	5
2015	7.77	5
2016	7.42	4

Figure 19. Wind power class each year.

VII. Specifications of the wind turbine

The wind turbine has a few important specifications which are necessary in order to understand how it works. The wind turbine works with two different generators, depending on the wind speed velocity. The generators have different synchronous velocities, which is the speed at which an induction motor will operate depending on the input power frequency and the number of electrical magnetic poles in the motor. The first generator is used in low wind speed velocities; it has 8 poles. Based in the equation 1 and the data provided from the display the wind turbine, this generator was spinning at 760 rpm. The rpm of the rotor related with this generator are 32.5 rpm. The second generator is used for high wind speed velocities. It has 6 poles and, using the same data sources, it was shown that it was spinning at 1006 rpm and the rotor at 43.5 rpm. The graph of Fig. 20 shows at what wind speed the wind turbine is changing from one generator to the other (7).

$$n(rpm) = \frac{60 * f(50\ hz)}{poles\ (pair\ of\ poles)} \qquad 1)$$

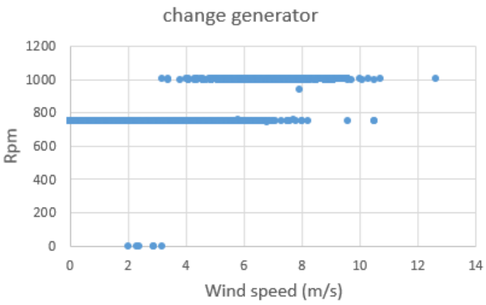

Figure 20. Generator distribution.

Another important specification it is the pitch regulated system of the wind turbine. The wind turbine turns its blades about the long axis (pitching the blades) to regulate the power extracted by the rotor (8).

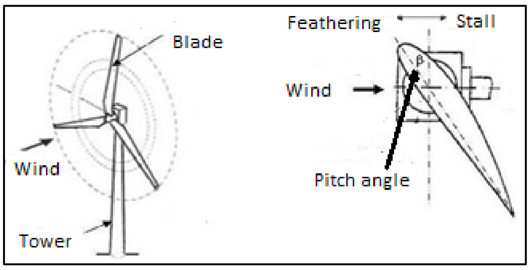

Figure 21. Pitch angle system.

VIII. Obtaining data

The main issue of this master thesis was to obtain data. After many attempts it was decided that the best way to take data is by taking photos of the display which is inside the wind turbine and that the main important data: wind speed, rpm rotor, rpm generator and power produced. Moreover, this display gives the power produced each month for the wind turbine which it is useful for this report. A Labview program was made in order to configure the data acquisition system in the laptop. The program takes photos each minute and stores them in a folder.

Figure 22. Data acquisition system.

IX. Power produced per month

The display of the turbine gives the power produced each month by the generator in Kwh and it is described in Fig. 23 that the months with the highest production of energy were in winter (February and January), which resembles Fig. 6 which shows that the months with highest wind speed are also in winter.

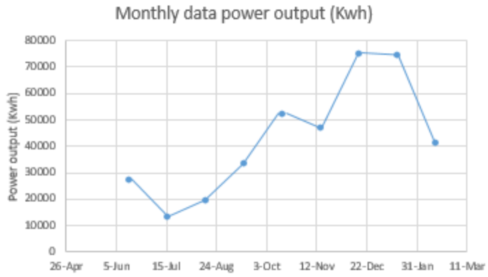

Figure 23. Power produced monthly.

X. Wind speed from nacelle vs. Windcube v2

The power curve of a wind turbine is a function based on two parameters: power and wind speed. In this thesis, two methods were used to obtain the wind speed. The first one is using the wind speed values from the anemometer which is situated in the nacelle of the wind turbine Fig. 24. The other way is using the data provided by Windcube v2.

Figure 24. Anemometer in the nacelle.

Figure 25. Location of Windcube v2.

The first thought was that the wind speed data from Windcube v2 should be used because the anemometer of the nacelle is situated behind the rotor and its measurements could be affected by the wake of it. Therefore, if the values from the anemometer is used, it has to be separated depending on the orientation of the wind during the days. The wind turbine which is assessed (red circle, Fig. 26) is affected by the wake effect of the other wind turbines (black circles, Fig. 26) when the wind is coming within the ranges of [140º - 180º] and [320º - 15º] but is not affected when coming from other directions. Therefore, these results give out two power curves, one affected by the wake and another one which is not affected (Fig. 28 and Fig.29).

In order to improve the accurancy of the analysis, the wind speed data from wind cube is synthesized in three different heights (18,31.5 and 45 m) which corresponds with the bottom of the blade, the hub height and the top of the blade respectively. As described in Fig.9, This is due to the wind profile slightly changing with height, so that the differents position of it during the asssesment need to be taken into account.

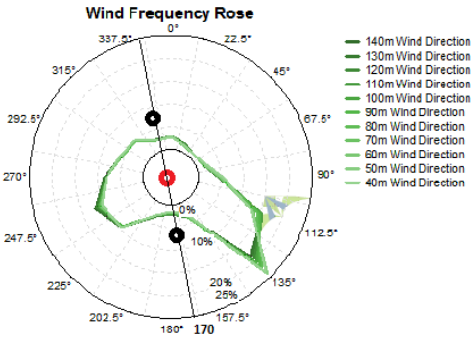

Figure 26. Wind turbines situated in wind rose (red one is analyzed).

Fig. 28 and Fig 29. shows that the curve not affected by the wake effect will produce more power with the same wind. However, more data is needed in order to support this hypothesis. They are compare with the power curve provided from the company Vestas for that turbine Fig 25.

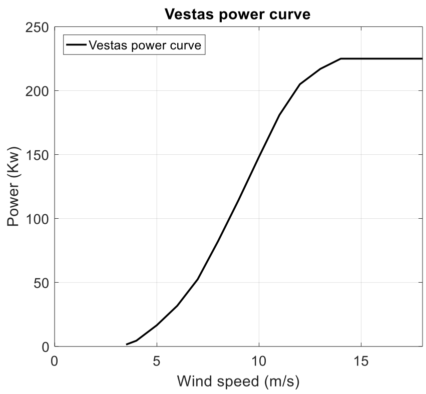

Figure 27. Power curve datasheet Vestas

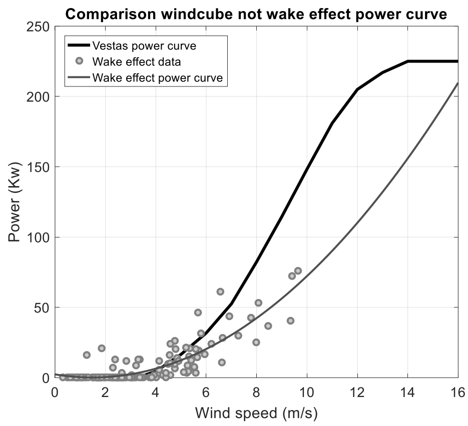

Figure 28. Power curve affected by the wake (grey).

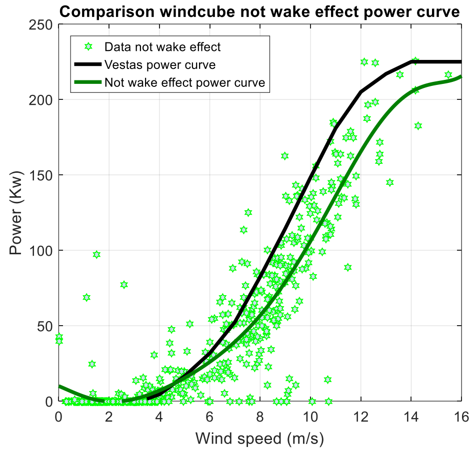

Figure 29. Power curve not affected by the wake (green).

XI. Power curve

After obtaining the data, the power curve was visualized (Fig. 30). The values used to obtain this power curve is 10 min data average taken from 1 min photo acquisition from the display inside the wind turbine. These results were obtained in 7 days during May 2016 (6-10th, 21-22th, 28-30th). The power curve shows that the turbine starts to produce power above 3,4 m/s. Based on the datasheet of Vestas, the nominal power of the wind turbine is reached at 14 m/s and stops at 25 m/s (stall conditions pitch angle Fig. 21).

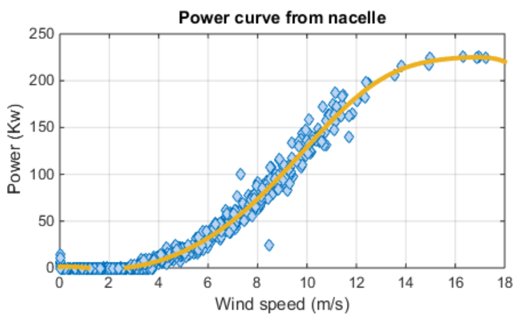

Figure 30. Wind power curve based on data from anemometer.

XII. Comparison of power curves

In order to decide which power curve is more reliable, they are compared with the power curve described on the data sheet of Vestas (black curve, Fig. 27). As seen in Fig. 31, the power curve based on the wind speed from the nacelle is closer to the one from Vestas's. Hence, this one will be used in the following points to analyze the wind turbine.

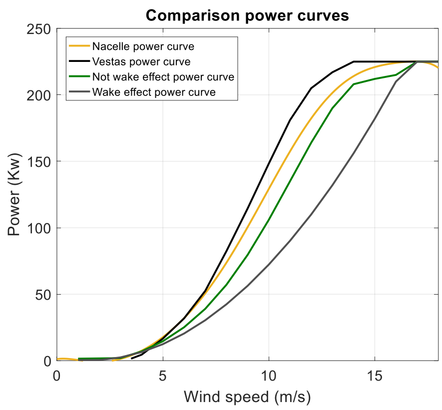

Figure 31. Comparison power curves with Vestas`s datasheet (black).

The power curve from the anemometer of the wind turbine is compared with another two, which are important to test the viability of the data provided for the wind turbine. First, it is compared with the theoretical power curve (red curve), which is the kinetic energy available that the wind can give without taking account the restrictions of the Betz´s law and is represented in equation 4 (6). This power curve is giving significantly more power than the one provided by the display, which is normal because usually the wind turbine is obtaining less than a half of the maximum power of the wind. If the wind turbine obtained all the kinetic energy form the wind, downstream the wind speed velocity would be 0 m/s. The second curve (black curve) is the one which is in the datasheet of Vestas. This power curve is really close to the one obtained experimentally. Therefore, obtained results is considered to be reliable.

$$P_{theoretical} = \frac{1}{2} * \rho * V^3 * \mathrm{A} \quad 4)$$

Where:

- ρ = mean air density = 1.224 kg/m^3.
- A = rotor´s area = 572 m^2.
- V = wind speed velocity form anemometer on the turbine (m/s).

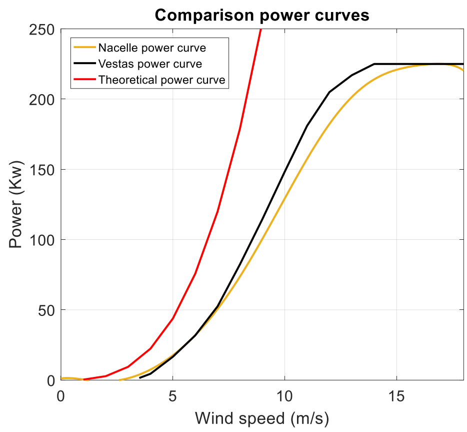

Figure 32. Comparison nacelle power curve (yellow) with Vestas's datasheet (black) and theoretical power (red).

XIII. Efficiency power curves

In this section, the efficiency of the power curve obtained experimentally and the one given by the datasheet of Vestas are compared. Both data sets are similar, however, the points used to obtain the curve are a little scattered. Although the points are dispersed, it is important to highlight that they are below 59% of efficiency, which is the maximum efficiency of a wind turbine based on the Betz´s law equation 6 (6). Then even if the points are scattered, it could be assumed that they are in the correct range. Maximum efficiency reached during the assessment is Cp = 58 %.

$$C_p = \frac{Extracted\ power}{Power\ in\ the\ wind} = \frac{P_{turb}}{\frac{1}{2} * \rho * V^3 * A} \quad 5)$$

$$C_p = \frac{2*\rho*A*V^2*a*(1-a)^2}{\frac{1}{2}*\rho*V^2*A}$$

$$\frac{dC_p}{da} = 0 \rightarrow a = \frac{1}{3}$$

$$C_p = 4*a*(1-\frac{1}{3})^2$$

$$C_p\left(a=\frac{1}{3}\right) = 4*\frac{1}{3}*\left(1-\frac{1}{3}\right)^2 = 59.3\% \quad 6)$$

Where:

- ρ = mean air density = 1.224 kg/m^3.
- A = rotor´s area = 572 m^2.
- V = wind speed velocity from anemometer (m/s).
- a = maximum axial induction factor $=\frac{1}{3}$.

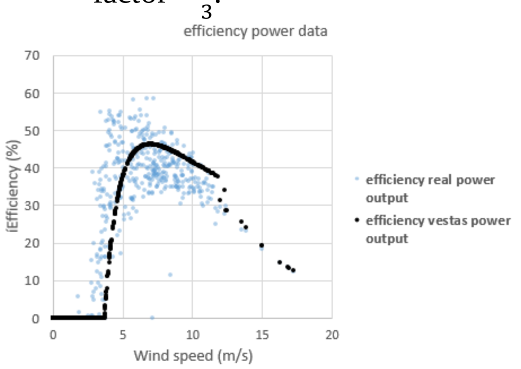

Figure 33. Efficiency power data.

XIV. Conclusion

The results of the wind analysis show that the windiest month in Ørland in 2015/2016 were in winter. The annual wind power class at 50m is cataloged as 4, described as ¨good¨, with a mean wind speed of 7.2 m/s and a density of 478 W/m2 (5). In long term extrapolation the values fit with the wind direction (135º, south-east direction) and with the mean wind speed result (6.83 m/s) at hub´s height (31.5 m.).

The outcome of the wind power analysis concludes that, in order to obtain the power curve of the wind turbine, the information provided by the anemometer on the nacelle, which is closer to the one provided by Vestas, is needed. The efficiency curve is also similar to the datasheet, although data is scattered. Moreover, its power production of the wind turbine was shown to decrease when it is affected by the wake effect of the other turbines.

XV. References

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